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Investigation of the effect of grain size on forming forces in Single Point Incremental Sheet Forming

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Abstract

Incremental Sheet Forming (ISF) is one of the manufacturing technologies to produce small batch sized components by moving a small size punch along the user defined path. This paper presents a theoretical, experimental and numerical study to find the effect of grain size on the forming forces in the ISF process. This is necessary as the actual sheets used for forming are not cystallographically uniform but contains some inherent impurities and defects, which leads to increase in hardness and conventional yield stress with an excessive reduction in ductility, which is due to change in grain boundaries. The grain size also increases with increase in temperature. Experiments are performed on samples heat treated at different temperatures and hence, different grains to evaluate the effect on forming forces. It is observed that the increase in grain size results in decrease in the peak value of forming force. An empirical model is proposed, which establishes the mathematical relationship between the forming force and forming depth, with change in grain size.

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*Keywords:*Incremental Sheet Forming; Grain Size; Forming Force

1. Introduction

Incremental Sheet Forming (ISF) is one such technique that is flexible and innovative for limited sheet metal component fabrication. The complete deformation is the sum total of small strains developed during each incremental step [1]. Although, ISF as a technology is far superior to conventional forming processes and carries significant advantages over them in terms of formability, flexibility and tooling cost, still, it has some serious drawbacks which constraints its implementation on shop floor and hinders it in reaching mainstream. As forming force helps us to determine the machine tool, punching tool and work piece material, along with the thickness of the work piece therefore its evaluation is necessary to select the optimal process parameters so as to reduce the process

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time [2]. Literature reports that the value of forming force depends on the parameters like wall inclination angle, incremental step depth, tool diameter and sheet thickness, to name a few, but in all such cases, crystallography of the sheet metal was not considered. It is also reported that the forming forces are very small in comparison to the deep drawing process and do not depend on the product size [3].

In this work, a theoretical, experimental and numerical study is performed to determine the forming load components in the ISF process. In this paper, the effect of grain size on forming forces in ISF is studied. The microscopic analysis of the samples reveals the presence of inherent impurities and defects in the metal. During pre-experimentation, with the help of Brinell hardness test and Uni-axial tensile test, it is observed that the original non-heat treated samples have higher hardness and conventional yield stress with significantly low ductility in comparison to heat treated samples. These results provide sufficient background to develop framework for further investigations in the domain of ISF. Further, a mathematical model is proposed to identify the effect of grain size of the sheet material on the forming forces in relation to forming depth.

2. Experimental Investigation

The material used in this work to perform the experiments is an Aluminium alloy 1050 sheet (AA1050A) with a melting point of 650 °C, which is work hardened by rolling to half hard. The sample is not annealed after rolling. Four samples of Aluminium sheet are prepared in this work. While three of them are subjected to temperatures of 230° C, 330° C and 500° C respectively for 60 minutes. Later, the samples are furnace cooled and brought to the room temperature. The fourth sample is left at the room temperature. The microstructure images are obtained by scanning electron microscope (SEM), as shown in Fig. 1. Later average grain size is evaluated with the help of MATLAB code [4]. Besides, the grain size also increases with increase in temperature.

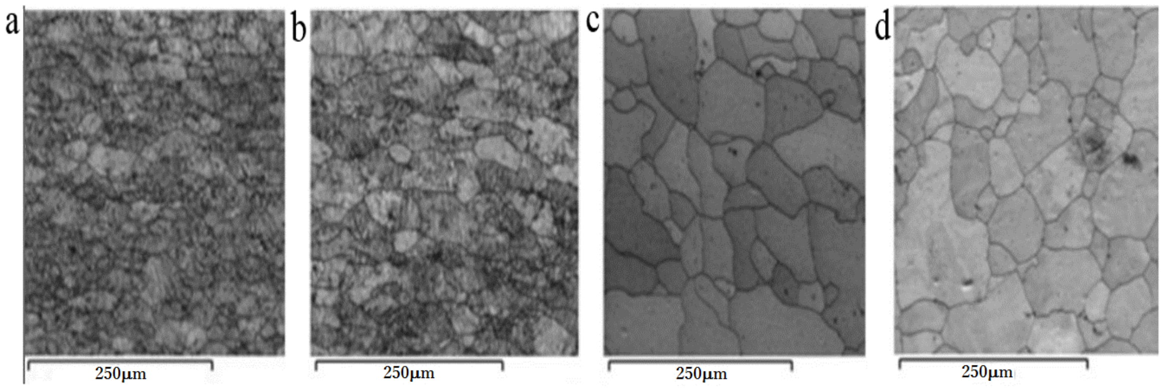

Fig. 1. SEM images showing metallography of different heat treated samples at (a) room temperature; (b) 230°C; (c) 330°C; (d) 500°C.

2.1. Hardness and tensile test

Brinell hardness test is performed with a sphere of weight 250 N and diameter 5 mm. Further, uni-axial tensile test under monotonic load is performed on dog-bone shaped specimens. Test specimen dimensions and tolerance specifications are as per the ASTM E8 standards and the variation in strain with grain size is depicted in Fig. 2. Table 1 summarizes the effect of heat treatment along with the cycle time for different test samples.

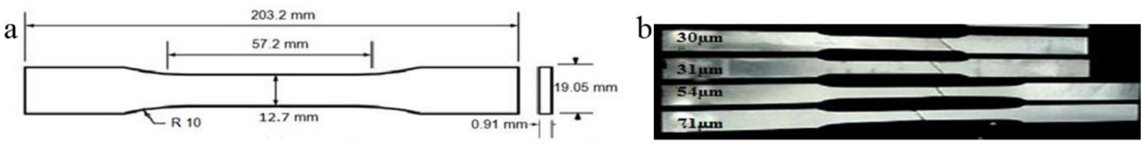

Fig. 2. (a) geometry of tensile test specimen; (b) effect of grain size on elongation up to fracture.

Table 1.Heat treatment effect.

Temperature(*°C*)	Exposure time(*min*)	Average Grain Size(*μm*)	BHN	Yield Stress(*MPa*)	Strain (%)
Room temperature	-	30	42	113.8	4.449
230	60	31	40	111.2	7.68
330	60	54	36	68.7	60.1
500	60	71	34	67.6	63.2

2.2. Incremental sheet forming process

All the tests are carried out on a 3-axis CNC milling machine. The size of the sheet metal has a diameter of 100 mm and a thickness 0.91 mm. It is clamped around its contour. The top plate had an orifice of 80 mm diameter where the blank could be formed. Industrial oil is used as a lubricant. The tool moved along a path that determined the contour of the required shape. In the present work, the tool path is a 3-dimensional spiral along the vertical axis with fixed vertical downward movement. The inward movement is followed simultaneously to form a truncated conical shell. Table 2 gives the values of referred ISF parameters as derived from the literature and the preliminary tests.

Table 2.Forming parameters.

Tool diameter (*mm*)	Vertical step size (*mm*)	Rotational speed (*RPM*)	Tool feed rate ($mm\ min^{-1}$)	Lubricating oil	Tool path
8	0.2	200	1000	Industrial oil	Spiral

2.3. Forming force

Special considerations are required to be given to the forming forces to achieve perfection and precision. The vertical component of the forming force (F_z) is the most critical. In order to study the force behaviour, 'Kistler', a piezoelectric dynamometer is placed below the sheet clamping frame. The geometry of the part, tool path trajectory considered and set up for force measurement is shown in Fig. 3. There are various technological parameters that influence the measured force directly [5].

Force measurement is done for the aforementioned process parameters and geometry in order to find the effect of grain size on the trend and peak value of vertical component of forming force. Forming force trend is measured for each of the sample separately, and its trend with the forming time and the depth of the specimen is measured.

a b

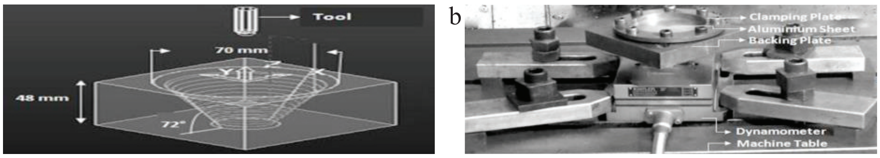

Fig. 3. (a) part geometry and tool path trajectory in ISF; (b) set up for measuring forming force.

Fig. 4 shows the relation between forming depth (z) and forming time (t) for referred truncated cone geometry. The relationship between forming time and depth of the geometry is worked out by fitting a cubic trend line.

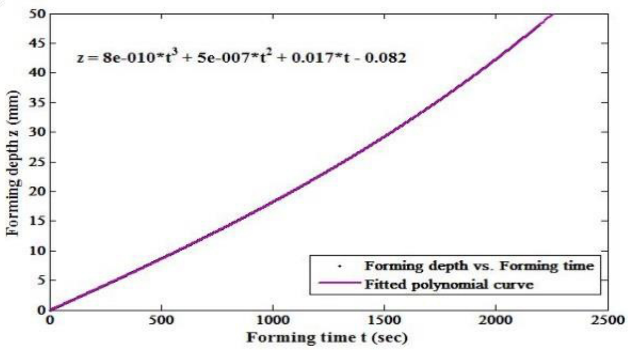

Fig. 4. relationship between forming depth and forming time for truncated cone geometry.

The variation in F_z with grain size is shown in Fig. 5. The trend of the curve is almost similar for all the samples except that the peak value of the forming force increases with decrease in grain size. This is due to decrease in dislocation density with coarse grains. The general trend of forming force versus forming depth can also be attributed due observation of the bending phenomenon up to the peak force value followed by initiation of stretching as well as thinning mechanism (as the sheet is fully clamped) with considerable sheet material wear leading to drop in forming force values. After certain depth, strain hardening develops in the sheet material, which leads to an increase in the forming load. Equilibrium between thinning and work hardening makes the forming load almost constant.

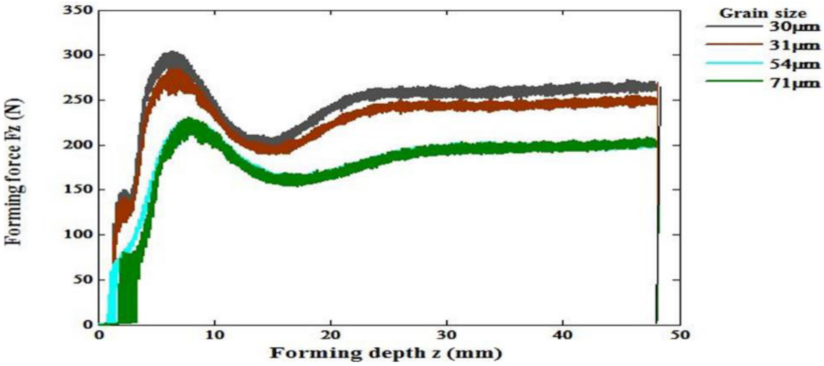

Fig. 5. Variation in forming force vs. forming depth with different grain size.

Equations (1) to (4) gives empirical relationships between the vertical component of forming force and forming depth for the grain sizes of 30 µm, 31 µm, 54 µm and 71 µm respectively, where for the present set of experiments the maximum forming depth is limited to 48 mm.

$$F_z = 166.3e^{-(\frac{z-4.912}{2.815})^2} + 263.3e^{-(\frac{z-44.3}{21.11})^2} + 169.9e^{-(\frac{z-20.48}{11.86})^2} + 156.2e^{-(\frac{z-8.71}{4.46})^2} \tag{1}$$

$$F_z = 152.9e^{-(\frac{z-5.07}{2.88})^2} + 246.9e^{-(\frac{z-44.4}{21})^2} + 145e^{-(\frac{z-8.99}{4.68})^2} + 158.1e^{-(\frac{z-20.74}{11.94})^2} \tag{2}$$

$$F_z = 165.8e^{-(\frac{z-7.86}{5.18})^2} + 199.6e^{-(\frac{z-46.38}{23.39})^2} + 9.58e^{-(\frac{z-34.39}{1.93})^2} + 166.5e^{-(\frac{z-20.53}{12.92})^2} \tag{3}$$

$$F_z = 176.5e^{-(\frac{z-8.05}{4.32})^2} + (1.9e+005)e^{-(\frac{z-41.45}{21.6})^2} + (-1.94e+005)e^{-(\frac{z-41.45}{21.61})^2} + 140.4e^{-(\frac{z-18.89}{11.27})^2} \tag{4}$$

3. Conclusion

During the course of experiments, it is observed that with heat treatment, an increase in grain size is observed with increase in temperature. Further, with increase in grain size, a decrement in hardness and yield stress, as well as increment in plasticity and ductility is observed. The investigation further revealed that when the metal sheets are subjected to a temperature of up to 230°C, there are marginal changes in the aforementioned properties. This may be attributed to an initial recovery process. The change, however, does not affect the structure and no appreciable increase in ductility is found. When the sheets are subjected to an elevated temperature then significantly higher changes are observed due to recrystallization phenomenon.

The experimentation helped to establish a correlation between the trend of the tensile test results and those of forming force in ISF. The forming forces decreases with an increase in the grain size, which eases the manufacturing process. Later, an empirical relation has been developed for different grain sizes of sheet material to estimate approximate value of forming forces.

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